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# Molecular Beam Assembled (MBA) Graphene Nanoribbons: Synthesis, Transport Study, and Flexible Electronics

Technical Proposal for Office of Naval Research
In response to BAA 11-001

Period of Performance: July 1, 2011 to June 30, 2014

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Date: 6-30-11

# Volume I - Technical Proposal

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## II. Technical Approach and Justification

### II. A. Executive Summary

**Objectives:** Graphene is a truly remarkable two-dimensional material with fascinating properties; however, the lack of a bandgap has hindered graphene from many electronic applications. To render a bandgap for room temperature operation, reliable production of graphene nanoribbons (GNRs) with width ~ 1-2 nm and atomically smooth edges would be of paramount importance, and may lead to opportunities for both fundamental research and important applications such as flexible electronics.

We propose to develop and investigate a novel molecular beam assembly (MBA) technology to produce graphene nanoribbons with nanometer width and atomically smooth edges. The objectives of this project are:

1. We will synthesize and characterize graphene nanoribbons with nanometer width and atomically smooth edges, including both armchair and zigzag edges;
2. We will carry out fundamental transport study on the MBA graphene nanoribbons, with particular focus on investigating the dependence of the nanoribbon bandgap on the structure (armchair v.s. zigzag edges) and ribbon width;
3. We will further develop graphene flexible electronics based on MBA GNRs and study their applications.

**Approach:**
For the first two objectives, we will take the following approach:

1. Design and synthesis of unique molecules that can self-assemble into GNRs,
2. Production and characterization of GNRs,
3. Transfer and fundamental transport study of GNR field effect transistors (FETs), and
4. Simulation of band structures and transistor properties of the MBA GNRs.

For the third objective, the following approach will be taken:

1. Synthesis of GNR network by using MBA.
2. Transfer of GNR network to flexible substrates using a roll-to-roll transfer technique.
3. Fabrication and characterization of flexible GNR transistors and circuits.

**Naval relevance:** This project is closely related to many naval applications. The proposed molecular beam assembly technology will render us a unique family of graphene nanoribbons with nanometer width and smooth edges, which can then be used as the active channel for flexible transistors or radio frequency (RF) transistors. While flexible graphene nanoribbon devices can be used to produce wearable electronics, which may be integrated into soldier uniforms and portable devices, nanoribbon RF transistors can find a wide variety of applications such as battle-field communication and remote imaging.

**Statement of Work:**
**Phase I (4 months):** Design and Synthesis of molecules for the molecular beam assembly process.
**Phase II (12 months):** Production of GNRs and characterization using Raman spectroscopy, scanning tunneling microscopy (STM), and atomic force microscopy (AFM).
**Phase III (12 months):** Transfer of graphene nanoribbons, device fabrication, and fundamental transport study of GNRs with both zigzag and armchair edges.
**Phase IV (8 months):** Transfer processing of GNR networks and flexible transistor fabrication and characterization.

## II. B. Background

Exceptional carrier mobility and current density in graphene make it highly promising material for future electronic devices[1, 2]. Furthermore, single atomic thickness provides ideal electrostatic geometry for field effect devices, which is critical for reducing short channel effects in deeply scaled down devices. However, graphene is a semi-metal with zero band gap, which limits its application in electronic devices. Quantum confinement and edge effects in narrow graphene nanoribbons (GNRs) have been proposed and demonstrated as a way to open band gap in graphene [3-7]. GNRs with sub 10 nm width are required to obtain bandgap relevant for room temperature electronic devices. Several fabrication approaches to obtain GNRs have been proposed and reported, such as lithographic methods for etching graphene films[6], nanowire shadow mask etching[8], chemical etching to shrink GNR size, chemically derived solution methods[7] and unzipping of carbon nanotubes[9, 10]. However, reliable fabrication of ultra narrow GNR with sub 10 nm width remains very challenging. Moreover, it has been theoretically predicted that any edge defects in such narrow GNRs would severely degrade its electronic properties, thus, ideal atomic edge smoothness is required to obtain GNR well behaving electronic devices[11, 12]. This requirement creates immense challenge for top down fabrication approaches.

Bottom up approaches of synthesis GNRs may offer much better control to obtain GNR with uniform width and atomically smooth edges. For example, synthesis of atomically precise GNRs by a surface assisted polymerization and dehydrogenation of monomer precursor molecules have been reported recently [13]. The topology, width and edge periphery of the GNRs should be further controlled by the structure of the precursor monomers. Similar bottom-up approaches have potential to produce uniform few nm wide GNRs at large scale. Such methods would further enable investigation of electron transport properties in ultra narrow GNRs, with further applications in low cost flexible electronics.

## II. C. Proposed Work

### II.C.1: Synthesis and characterization

**Molecular Beam Assembly** Unique molecules will be designed for the synthesis of both zigzag and armchair GNRs. As shown in Figure 1a, two kinds of monomers 1 and 2 will form 3 through dehalogenation reaction. The synthesis will be carried out by Prof. Mark Thompson and his research group. Molecule 3 will then be used as a precursor, sublimed from a high vacuum evaporator onto receiving substrate. Single crystal Au (111) on mica will be used as receiving substrate, and will be heated constantly for precursor dehalogenation to form molecule 4. After depositing precursor molecules, the substrate will be raised to higher temperature for self-assembled dehydrogenation and form GNRs with zigzag edges.

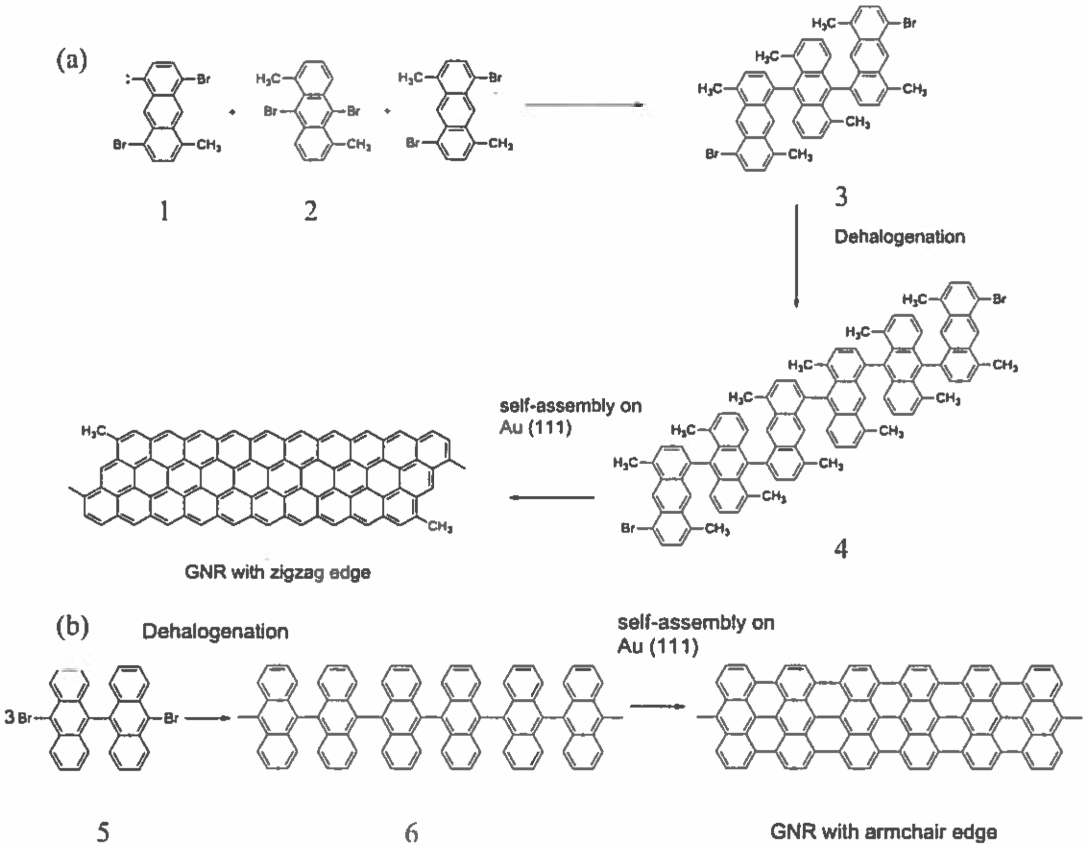


Figure 1. Synthetic routes for graphene nanoribbons with zigzag edges (a) and armchair edges (b).

GNRs with armchair edges will also be synthesized by choosing different starting precursor monomers. Previously reported precursor monomer 5 was used by Cai et al[13] for the synthesis of armchair GNRs. As shown in Figure 1b, precursor molecule 5 deposited on Au (111) substrate will dehalogenate and form molecule 6. After a self-assembly process, molecule 6 will lose hydrogen to assembly into GNRs with armchair edges.

We will study the temperature effect on the formation of GNRs by applying different temperatures (100 °C to 300 °C) to Au (111) substrates while depositing precursor molecules.

**Characterization by Raman spectroscopy and STM**

We plan to use Raman spectroscopy for the characterization of GNRs (figure 2a). A typical Raman spectrum is shown in figure 2b, which is capable to provide the information of the quality of GNRs. STM is also proposed to use for the characterization of GNRs before and after dehydrogenation. Previous study by Cai et al[13] has used STM to successfully characterize the structure of GNRs before and after dehydrogenation, shown in figure 2a and 2b, respectively.

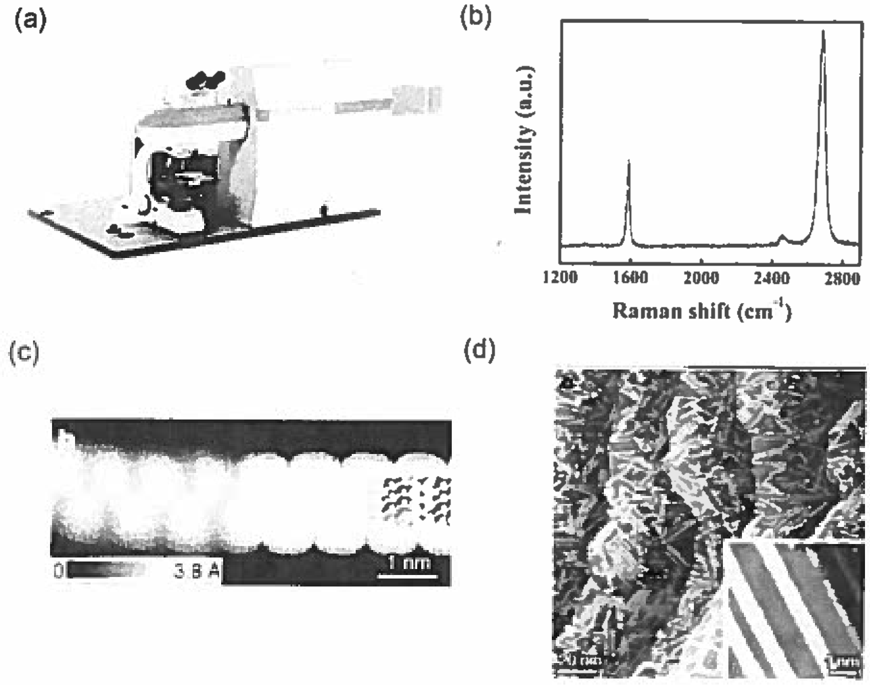


Figure 2. Characterization of GNRs by Raman spectroscopy and STM. (a) A photo image of our Renishaw Raman microscope. (b) Typical Raman spectrum of graphene. (c) STM image after deposition of precursor molecules but before dehydrogenation (from Ref. 13). (d) STM image of GNRs after dehydrogenation at 400 °C (from Ref. 13).

## II.C.2: Fundamental Transport Study

**Transfer of GNRs to target substrates** The as-grown GNRs are on Au (111)/Mica substrate, which is not useful for device fabrication. We will apply a transfer technique to transfer GNRs from Au (111) to any target substrates. Figure 3 shows the schematic diagram of the transfer process. GNRs on Au (111) are coated by a thin layer of PMMA. PMMA film is baked at 120 °C and the layered structure will be placed into gold etchant to remove gold, and then the PMMA/GNRs film will be free standing in gold etchant. The PMMA/GNRs film will then be transferred onto a target substrate, and acetone vapor will be used to remove the PMMA thin film, leaving only GNRs on top of the receiving substrate. We plan to transfer GNRs onto $SiO_2$/Si substrate where FETs will be fabricated for fundamental transport study.

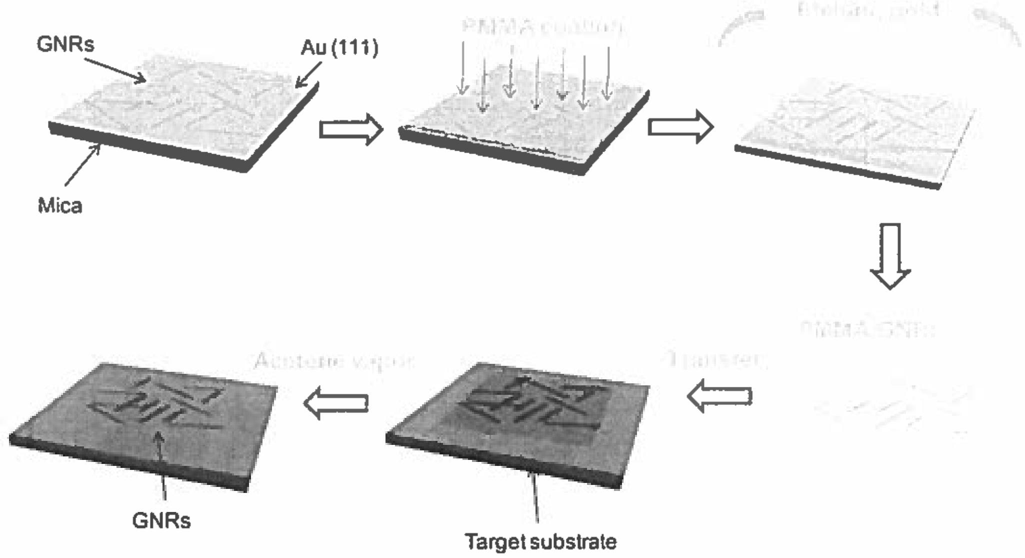


Figure 3. Schematic diagram of transfer technique. As-grown GNRs on Au (111)/Mica is coated with PMMA, gold is etched by gold etchant, and then PMMA/GNRs film will be placed on target substrate. PMMA will be removed by acetone vapor, leaving only GNRs on target substrate.

**Electron transport study** Theoretical results in the first (tight binding) approximation predict GNR to be metallic or semiconducting depending ribbon direction, zig-zag or armchair edge, and ribbon width. More careful first principle calculations predict that armchair GRNs are divided into 3 types with large, medium and small band gap openings, as shown in the Figure 4a-c. First principle calculation for zigzag GNRs, shown in Figure 4d-e, predict to have a small band gap opening [3]. Limited experimental results typically show all semiconducting behavior[5, 6], which could be complicated by edge roughness, edge passivation atoms and defects. We plan to experimentally investigate the fundamental electron transport in atomically smooth uniform GNRs, obtained in the molecular beam assembly (MBA) approach. Synthesis and transfer of dense arrays of GNRs would provide simple registration free fabrication of large number of GNR transistors, which would further enable systematic study of electron transport in ultra narrow GNRs. We will control the edge direction and width of GNRs by controlling the precursor monomer molecules and MBA conditions. By ambient and low temperature electrical measurements, we will extract the fundamental properties of GNRs and GNR transistors, such as band gap, number of conducting electron modes, mobility, doping levels, contact resistance and so on. By comparing the electrical measurement results for different types of GNRs and statistical analysis of large number GNR devices, we plan to verify the theoretical predictions. Developing fundamental understanding of electron transport in GNRs will be essential for further applications, such as flexible electronics.

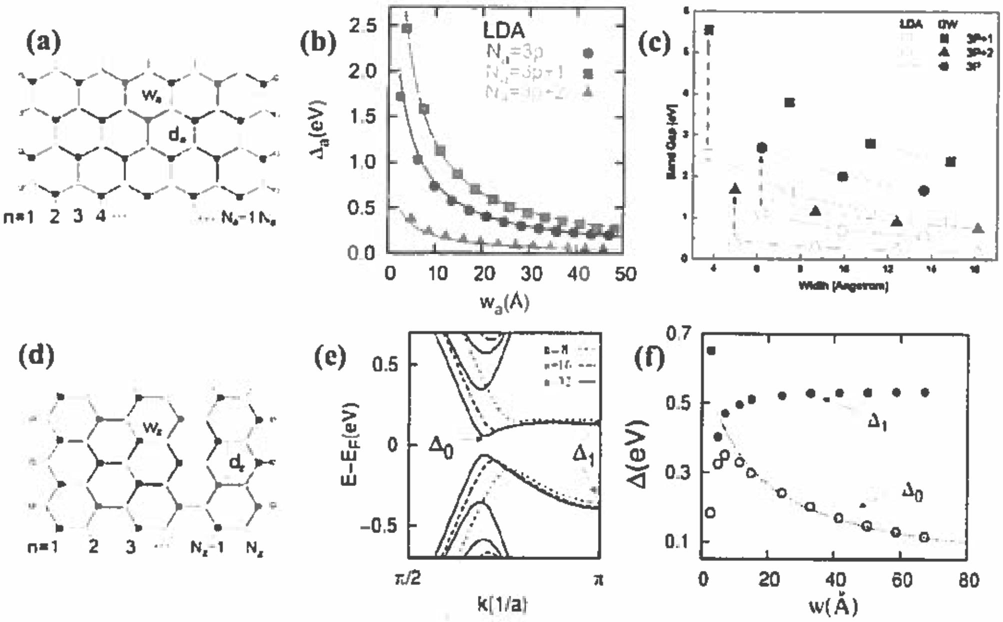

Figure 4. (a) Schematic diagram of a GNR section with armchair edge. (b),(c) First principle calculation of band gap in armchair GNR with different methods. (d) Schematic diagram of a GNR section with zigzag edge. (e), (f) First principle calculation of band gap in zigzag GNR. (from Ref. 3).

**GNR-based Flexible Electronics** GNRs synthesized by MBA can be transferred onto flexible substrate over large scale by a roll-to-roll printing process. Figure 5b shows a schematic diagram of the roll-to-roll transfer technique. Thermal release tape will be used to attach onto the surface of GNR/Au (111), by heating up the tape between two rollers, GNRs will be transferred to target flexible substrate. The as-transferred GNRs on flexible substrate facilitate the application for active-matrix organic light-emitting diode (AMOLED) or organic photovoltaics (OPVs). Figure 5c shows an illustration of a GNR-based AMOLED. Transport study will be performed for the GNR-OLED transistors, controlling of AMOLED to be turned on and off will be demonstrated which is similar to figure 5d.[14] We will also test the flexibility of the GNR AMOLED by conducting a bending experiment. 100 cycles of bending will be performed on the GNR AMLED transistors, sheet resistance will be measured after each bending cycle, OLED performance will be tested after bending cycles. We expect that our GNR-based flexible electronics will have high performance and open a way for the application of flexible AMOLED display.

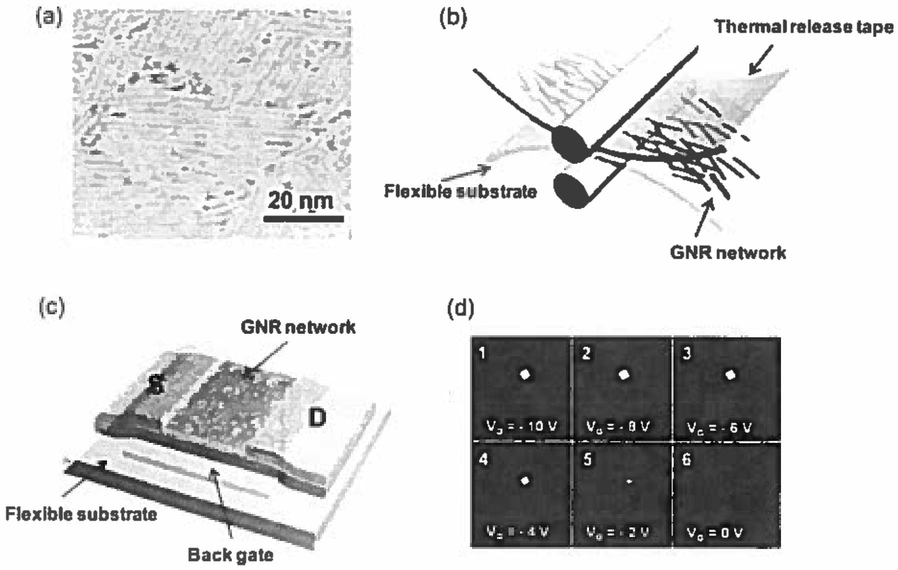


Figure 5. GNR network based flexible electronics. (a) STM image of as-grown GNR network on Au (111) (from Ref. 13). (b) Roll-to roll transfer of large-scale GNR network onto flexible substrate. (c) Fabrication of flexible graphene nanoribbon transistor. (d) Photographs of an OLED driven by nanotube thin-film transistors under different inputs showing turn-on and turn-off of the OLED.

## III. Project Schedule and Milestones

Figure 6 shows the project schedule and milestones. In the proposed project, milestones will be: in year #1, we will achieve the synthesis of both armchair and zigzag GNRs, with characterization and confirmation of both edges. In year #2, we will transfer the as-grown GNRs and fabricate FETs. Transport study will also be conducted for understanding of electrical properties of both armchair and zigzag GNRs. In year #3, we will achieve the fabrication of GNR-based flexible electronics by using the roll-to-roll transfer technique, bending experiments will be performed for the test of flexibility of our GNR-based flexible electronics.

| Project Schedule and Milestones | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Program tasks | | YEAR-1 | | | | YEAR-2 | | | | YEAR-3 | | | | Milestones |
| | | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | |
| 1 | **Synthesis and Characterization of GNRs** | | | | | | | | | | | | | Achieve the synthesis of both armchair and zigzag GNRs |
| 1.1 | MBA method for the synthesis of GNRs | ■ | ■ | ■ | ■ | ■ | | | | ■ | | | | |
| 1.2 | Raman spectroscopy and STM characterization of GNRs | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | | | |
| 2 | **Fundamental Transport Study** | | | | | | | | | | | | | Study transport properties for both armchair and zigzag GNRs |
| 2.1 | Transfer of GNRs to target substrates | | | | | ■ | ■ | | | | | | | |
| 2.2 | Electron transport study | | | | | | | ■ | ■ | | | | | |
| 3 | **GNR-based Flexible Electronics** | | | | | | | | | | | | | Fabricate flexible electronics by using GNR network |
| 3.1 | Roll-to roll transfer process of large-scale GNR network | | | | | | | | | ■ | ■ | | | |
| 3.2 | Device fabrication and flexible electronics | | | | | | | | | | ■ | ■ | ■ | |
| 4 | **Report** | | | | | | | | | | | | | |
| 4.1 | Progress report | ▼ | ▼ | ▼ | ▼ | ▼ | ▼ | ▼ | ▼ | ▼ | ▼ | ▼ | ▼ | |
| 4.2 | Final report | | | | | | | | | | | | ■ | |

Figure 6. Project schedule and Milestones.

## IV. Reports

We plan to report quarterly for technical and financial progress, and final report will also be scheduled.

## V. Management approach

The proposed project will involve Prof. Chongwu Zhou as the principal investigator (PI), and Prof. Mark Thompson as a Co-PI. Additionally, two graduate students will be funded to work on the project.

Through research centers present on USC's campus, Dr. Zhou and his Nanotechnology Research Laboratory have access to high-end experimental facilities and metrology tools: 1. The Keck Photonics Center hosts state-of-the-art fabrication facilities, including LPCVD furnaces, evaporators and instruments for photolithography, reactive ion etching and e-beam lithography. Dr. Zhou's group also maintains an active account with Stanford Nanofabrication Facility (SNF), and this venue can be used if additional fabrication capabilities are needed.2. The Microscope center hosts three transmission electron microscopes (TEMs) (regular and high resolution), two scanning electron microscopes (SEMs) and a variety of equipment for material analysis such as x-ray diffraction (XRD), x-ray photoelectron spectroscopy (XPS), and Auger analysis. Both the TEMs and SEMs are equipped with energy dispersive x-ray spectroscopy (EDX) capabilities. Additionally, Dr.

Zhou's lab hosts a large array of equipment for nanowire synthesis, device fabrication and characterization, and chemical and bio- sensing studies. Among the relevant list of equipment, we have a cluster tool consisting of four furnaces and a laser ablation system for the synthesis of various nanomaterials such as carbon nanotubes, metal oxide nanowires and nitride nanowires, a home-made chemical sensing setup with electrical feedthroughs, gas inlet and outlet, a view port for UV recovery, and an evacuation port connected to a turbo pump. The sensor can be easily loaded inside and exposed to various chemicals with a broad range of concentrations. The lab also includes an IO-Tech Data Acquisition (DAQ) System for electronic measurements, an Agilent 4156B precision semiconductor parameter analyzer for comprehensive electronic measurements of nanowire devices, an Atomic force microscope (Digital Instruments, Dimension 3100), a scanning electron microscope (JEOL 848) converted to do e-beam writing, a thermal evaporator for deposition of special materials, a probe station (Wentworth) for electronic device characterization, two H/P 4145B semiconductor parameter analyzers for electronic measurements, a Keithley 2400 / Keithley 237 combo for electronic measurements, and two cryostats (Desert Cryogenics) for low-temperature electronic measurements.

## VI. Qualifications

**Professor Chongwu Zhou** is currently a Full Professor at Department of Electrical Engineering of University of Southern California (USC). He is an Associate Editor for IEEE Transactions on Nanotechnology. He received PhD in 1999 from Yale University, where he did research with Prof. Mark Reed. He then worked as a postdoc with Professor Hongjie Dai at Stanford University from 1999 to 2000. He joined USC faculty in 2000.

Dr. Zhou has authored ~122 journal publications with altogether 10,916 citations as of 06/28/2011. His research interest covers graphene, carbon nanotubes, nanowires, and bionanotechnology. He has won a number of awards, including the NSF CAREER Award (2002), the NASA TGIR Award (2002), the USC Junior Faculty Research Award (2004), and the first IEEE Nanotechnology Early Career Award (2007).

Dr. Zhou was the first to report wafer-scale chemical vapor deposition (CVD) synthesis of graphene in 2009. He was also one of the first to report transfer of CVD graphene and device study, as well as the use of graphene as flexible transparent conductors.

In addition, he has made significant contribution to carbon nanotube nanoelectronics and macroelectronics. He was one of the first to report the synthesis of massively aligned carbon nanotubes on sapphire, and he developed wafer-scale synthesis, transfer, and integration of aligned nanotube devices and circuits. His recent contribution includes the development of thin film transistors and macroelectronics based on separated nanotubes.

Dr. Zhou has contributed significantly to education, service and outreach activities. He has developed a new class titled "Nanoscience and Nanotechnology", which is offered to and well received by USC students. He is a strong advocate for nanotechnology in southern California and currently serves on the Biomedical Nanoscience Initiative Committee of USC. He has advised many students at graduate, undergraduate and high school levels, including women and minorities.

**Prof. Thompson** is currently a professor of Chemistry department at the University of Southern California (USC). He received his Ph.D. in 1985 from California Institute of Technology, where he did research with Prof. John E. Bercaw, involving organoscandium chemistry. His current research interests involve the optical and optoelectronic properties of molecular materials and devices, particularly organic LEDs and solar cells, as well as nanoscale materials, catalysis and biosensors. Prof. Thompson has over 250 peer reviewed publications, and greater than 120 issued US patents. *He has ranked 12th in Thomson Reuters' Science Watch list as one of the world's most influential chemists.*

## VII. References


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## VIII. Current and Pending Project and Proposal Submissions

**Current and Pending Support for Prof. Chongwu Zhou:**

**Current Support:**

Project/Proposal Title: Center on Functional Engineered Nano Architectonics (FENA)
Source of Support: SRC MARCO/UCLA Total Award Amount: $403,325
Total Award Period Covered: 11/01/2009 – 10/31/2012
Technical contact: Prof. Chongwu Zhou Percentage effort: 0.5 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Joint KACST/California Center of Excellence on Nano Science and Engineering for Green and Clean Technologies
Source of Support: UCLA/King Abdulaziz City for Science & Technology
Total Award Amount: $846,000
Total Award Period Covered: 08/11/2009 – 08/10/2012
Technical contact: Prof. Chongwu Zhou Percentage effort: 1.0 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Energy Frontier Research Center – Emerging Materials for Solar Energy Conversion and Solid State Lighting
Source of Support: Department of Energy
Total Award Amount: $12,500,000
Total Award Period Covered: 08/01/2009 – 07/31/2014
Technical contact: Prof. Chongwu Zhou Percentage effort: 1.0 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Collaborative Research: Design, Modeling, Automation and Experimentation of Imperfection-Immune Carbon Nanotube Field Effect Transistor Circuits
Source of Support: National Science Foundation Total Award Amount: $318,088
Total Award Period Covered: 08/01/2007 – 07/31/2011
Technical contact: Prof. Chongwu Zhou Percentage effort: 0.75 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Multiplexed Nanosensing for DNA and Proteins
Source of Support: National Institute of Health Total Award Amount: $203,101
Total Award Period Covered: 02/01/2009 – 08/31/2011
Technical contact: Prof. Chongwu Zhou Percentage effort: 1.0 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Radiation Effects on Electronics in Aligned Carbon Nanotube Technology (RadCNT)
Source of Support: DTRA Total Award Amount: $1,050,000
Total Award Period Covered: 03/22/2010 – 03/21/2013
Technical contact: Prof. Chongwu Zhou Percentage effort: 0.5 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Collaborative Research: Nanostructure Growth Process Modeling and Efficient Experimental Strategies for Repeatable Fabrication of Bio-nanosensors
Source of Support: National Science Foundation Total Award Amount: $333,001

Total Award Period Covered: 08/15/2010 – 07/31/2013
Technical contact: Prof. Chongwu Zhou Percentage effort: 0.0 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Whittier Nanobiotechnology Program: Development of Novel Diagnostic Platforms using Nanosensors
Source of Support: L.K. Whittier Foundation Total Award Amount: $300,000
Total Award Period Covered: 07/12/2007 – 06/30/2011
Technical contact: Prof. Chongwu Zhou Percentage effort: 0.0 summer month
Relevance and Overlap: The project has no overlap with this proposal

**Pending Support:**

Project/Proposal Title: SNM: Scalable Nanomanufacturing and Nanoinformatics for Nanowire-Based Light-Emitting Diodes
Source of Support: National Science Foundation
Proposed Award Amount: $1,999,999
Proposed Duration of Project: 08/16/2011 – 08/15/2015
Technical contact: Prof. Chongwu Zhou Percentage effort: 0.25 summer month
Relevance and Overlap: The project has no overlap with this proposal

**Current and Pending Support for Prof. Mark E. Thompson:**

**Current Support:**

Project/Proposal Title: Detection of Biological Molecules Using Nanobiosensors
Source of Support: LK Whittier Foundation Total Award Amount: $140,000
Total Award Period Covered: 07/01/09-06/30/29
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.15 calendar month, 0.0 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Research on Advanced Organic Thin Film Electroluminescent Devices and Related Applications
Source of Support: Universal Display Corporation Total Award Amount: $12,092,590
Total Award Period Covered: 05/01/06 – 04/30/13
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 0.15 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Thin Film Solid State Organic Energy Conversion Devices
Source of Support: Global Photonics Energy Corporation
Total Award Amount: $9,083,595
Total Award Period Covered: 05/01/06 – 04/30/13
Location of Project: University of Southern California / Co-PI's: S. Forrest
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 0.16 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: An Engineering Research Center for Biomimetic Microelectronic Systems
Source of Support: National Science Foundation Total Award Amount: $17,000,000
Total Award Period Covered: 09/01/03 – 08/31/11
Location of Project: University of Southern California / PI: M. Humayun, Co-PI: G. Loeb
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 0.04 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: MRI: Acquisition of a 600 MHz NMR Spectrometer at the University of Southern California
Source of Support: National Science Foundation Total Award Amount: $538,270
Total Award Period Covered: 08/01/08 – 07/31/11
Location of Project: University of Southern California / PI: R. Roberts
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 0.0 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Energy Frontier Research Center – Emerging Materials for Solar Energy Conversion and Solid State Lighting
Source of Support: Department of Energy Total Award Amount: $12,500,000
Total Award Period Covered: 09/01/09 – 08/31/14
Location of Project: University of Southern California / PI: D. Dapkus
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 1.0 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Center for Advanced Molecular Photovoltaics
Source of Support: Stanford / King Abdullah University of Science and Technology (KAUST) – Prime Total Award Amount: $1,559,418
Total Award Period Covered: 07/07/08 – 06/30/13
Location of Project: University of Southern California / PI: M. McGehee
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.48 calendar month, 0.0 summer month for PI
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Hemispherical Organic Focal Plane Arrays: A New Architecture for Ultra Lightweight, Ultra Compact Imagers
Source of Support: Defense Advanced Research Projects Agency (DARPA)
Total Award Amount: $800,698
Total Award Period Covered: 09/09/08 – 06/08/12
Location of Project: University of Southern California / PI: S. Forrest
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 0.15 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Multiplexed Nanosensing for DNA and Proteins
Source of Support: National Institute of Health Total Award Amount: $581,533
Total Award Period Covered: 02/01/09 – 08/31/11
Location of Project: University of Southern California / Miami / PI: R. Cote

Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 0.12 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Collaborative Research: Acquisition of a 400 MHz NMR at the University of Southern California
Source of Support: National Science Foundation Total Award Amount: $469,164
Total Award Period Covered: 07/01/09 – 06/30/12
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 0.0 summer month
Relevance and Overlap: The project has no overlap with this proposal

Project/Proposal Title: Smart Biomaterial for Reversible Attachment to Central Nervous System
Source of Support: National Institutes of Health
Total Award Amount: $2,096,665.00
Total Award Period Covered: 12/01/10 – 11/30/13
Location of Project: University of Southern California / PI: J. Weiland
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 0.0 summer month

Project/Proposal Title: Smart SOLAR: Ultrabroad spectral bandwidth excitonic thin film solar cells based on carbon nanotubes
Source of Support: National Science Foundation Total Award Amount: $565,000
Total Award Period Covered: 09/01/09 – 08/31/12
Location of Project: Ann Arbor, MI and Los Angeles, CA / PI: S. Forrest
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.36 calendar month, 0.0 summer month

Project/Proposal Title: Acquisition of an X-Ray Diffractometer at the University of Southern California
Source of Support: National Science Foundation Total Award Amount: $484,455
Total Award Period Covered: 03/01/11 – 02/28/14
Location of Project: University of Southern California / PI: C. McKenna
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 0.0 summer month

**Pending Support:**

Project/Proposal Title: Toward an Affinity Reagent Pipeline: Targeting the Human Kinome via mRNA
Source of Support: National Institutes of Health Total Award Amount: $3,926,350
Total Award Period Covered: 09/01/11 – 08/31/14
Technical contact: Prof. Mark E. Thompson
Percentage effort: 0.0 calendar month, 0.18 academic month, 0.0 summer month

**Chongwu (Dave) Zhou (biosketch)**
Professor
Department of Electrical Engineering
University of Southern California, Los Angeles, CA 90089
Phone: 213 740 4708; Fax: 213 740 5696; Email: chongwuz@usc.edu;
http://nanolab.usc.edu/

**Education**

| | | | |
|---|---|---|---|
| Stanford University (Advisor: Hongjie Dai) | Postdoc | 2000 | Chemistry |
| Yale University (Advisor: Mark Reed) | Ph. D. | 1999 | Electrical Engineering |
| Univ. of Science and Technology of China | B. S. | 1993 | Physics |

**Employment**

| | |
|---|---|
| 2011 – Present | Professor of Electrical Engineering, with joint appointment in Physics, Chemistry, and Materials Science, University of Southern California |
| 2000 – 2011 | Assistant / Associate Professor of Electrical Engineering, University of Southern California |
| 1998 – 2000 | Postdoctoral Research Fellow, Department of Chemistry, Stanford University |

**Research Interests**

- **Graphene**: CVD synthesis and electronic applications (RF and flexible) of graphene.
- **Carbon Nanotubes**: synthesis, assembly and integration of single-walled carbon nanotubes for high-performance nanoelectronics and macroelectronics.
- **Nanowires**: synthesis of nanowires and applications for tandem solar cells and high-capacity lithium batteries.
- **Bionanotechnology**: Development of nano biosensor chips for biomedical research.

**Awards**

- Powell Award 2001
- NSF CAREER Award 2002
- Zumberge Interdisciplinary Research Award 2002
- NASA TGIR Award 2002 – "for exceptional progress toward the technology innovation"
- Norris Fellowship 2003
- USC Junior Faculty Research Award 2004
- IEEE Nanotechnology Early Career Award (2007)

**Professional Associations**

American Physical Society    Material Research Society    IEEE

**Selected Service Activities**

- 08/2006 – Present, Associate Editor for *IEEE Transactions on Nanotechnology*.
- 03/2005, served as the lead organizer for the DMP Focus Session: "Nanotubes and Nanowires: Devices and Applications" for APS March 2005 Meeting.
- 07/2005, served as the lead organizer for the Session "Inorganic Nanowires" for IEEE NANO 2005 Conference.

**Selected Publications:** Zhou has published ~122 journal papers with altogether 10,916 citations.

1. "Comparison of Graphene Growth on Single-Crystalline and Polycrystalline Ni by Chemical Vapor Deposition", Y. Zhang, L. Gomez, F. Ishikawa, A. Madaria, K. Ryu, C. Wang, A, Badmaev, and **C. Zhou, Journal of Physical Chemistry Letters**, 1, 3101–3107 (2010)

2. "Continuous, Highly Flexible, and Transparent Graphene Films by Chemical Vapor Deposition for Organic Photovoltaics", L. Gomez, Y. Zhang, C. W. Schlenker, K. Ryu, **M. E. Thompson, C. Zhou, ACS Nano**, 4, 2865 (2010).
3. "Synthesis, Transfer, and Devices of Single- and Few-Layer Graphene by Chemical Vapor Deposition", L. Gomez, Y. Zhang, A. Kumar, **C. Zhou, IEEE Transactions on Nanotechnology**, 8, 135 (2009).
4. "CMOS-Analogous Wafer-Scale Nanotube-on-Insulator Approach for Submicrometer Devices and Integrated Circuits Using Aligned Nanotubes", K. Ryu, A. Badmaev, C. Wang, A. Lin, N. Patil, L. Gomez, A. Kumar, S. Mitra, H. Wong, **C. Zhou, Nano Letters**, 9, 189 (2009).
5. "Scalable Light-Induced Metal to Semiconductor Conversion of Carbon Nanotubes", L. Gomez, A. Kumar, Y. Zhang, K. Ryu, A. Badmaev, **C. Zhou, Nano Letters**, 9, 3592 (2009).
6. "Wafer-Scale Fabrication of Separated Carbon Nanotube Thin-Film Transistors for Display Applications", C. Wang, J. Zhang, K. Ryu, A. Badmaev, L. Gomez, **C. Zhou, Nano Letters**, 9, 4285 (2009).
7. "Fabrication of Fully Transparent Nanowire Transistors for Transparent and Flexible Electronics", S. Ju, A. Facchetti, Y. Xuan, J. Liu, F. Ishikawa, P. Ye, **C. Zhou**, T. J. Marks, and D. B. Janes, **Nature Nanotechnology**, 2, 378-384 (2007)
8. "Template-Free Directional Growth of Single-Walled Carbon Nanotubes on a- and r-Plane Sapphire", S. Han, X. Liu, and **C. Zhou, Journal of the American Chemical. Society**, 127, 5294 (2005).
9. "Nanotube Molecular Wires as Chemical Sensors", J. Kong, N. Franklin, **C. Zhou**, S. Peng, K. Cho, H. Dai, **Science**, 287, 622 (2000).
10. "Modulated Chemical Doping of Individual Carbon Nanotubes", **C. Zhou**, J. Kong, E. Yenilmez, and H. Dai, **Science** 290, 1552 (2000).

Synergistic Activities

Dr. Chongwu Zhou is currently a Full Professor at Department of Electrical Engineering of University of Southern California (USC). He is an Associate Editor for IEEE Transactions on Nanotechnology.

Dr. Zhou has authored ~122 journal publications with altogether 10,916 citations as of 06/28/2011. His research interest covers graphene, carbon nanotubes, nanowires, and bionanotechnology. He has won a number of awards, including the NSF CAREER Award (2002), the NASA TGIR Award (2002), the USC Junior Faculty Research Award (2004), and the first IEEE Nanotechnology Early Career Award (2007).

Dr. Zhou was the first to report wafer-scale chemical vapor deposition (CVD) synthesis of graphene in 2009. He was also one of the first to report transfer of CVD graphene and device study, as well as the use of graphene as flexible transparent conductors.

In addition, he has made significant contribution to carbon nanotube nanoelectronics and macroelectronics. He was one of the first to report the synthesis of massively aligned carbon nanotubes on sapphire, and he developed wafer-scale synthesis, transfer, and integration of aligned nanotube devices and circuits. His recent contribution includes the development of thin film transistors and macroelectronics based on separated nanotubes.

Collaborators

Prof. Kang Wang (UCLA), Prof. Mark Thompson (USC),
Prof. Richard Cote (USC), Prof. Philip Wong (Stanford)

## Mark Edward Thompson (biosketch)

Department of Chemistry
University of Southern California
Los Angeles, CA 90089-0744
phone: (213) 740-6402; fax: (213) 740-8594; E-mail: met@usc.edu

**Education:**

| | |
|---|---|
| 1985 | California Institute of Technology, Pasadena, CA. Ph.D. in inorganic chemistry. Thesis research with Prof. John E. Bercaw, involving organoscandium chemistry. |
| 1980 | University of California at Berkeley. B.S. with honors in chemistry. |

**Professional Experience:**

| | |
|---|---|
| 2005-2008 | University of Southern California, Chemistry Department Chairman |
| 1998-now | University of Southern California, Department of Chemical Engineering and Materials Science, joint appointment |
| 1999-now | University of Southern California, Department of Chemistry, Professor |
| 1995-1999 | University of Southern California, Department of Chemistry, Associate Professor |
| 1987-95 | Princeton University, Princeton, NJ. Assistant Professor. |
| 1985-87 | Inorganic Chemistry Laboratory, Oxford University, Oxford, England. S.E.R.C. Research Fellow. Worked with Prof. Malcolm L.H. Green, studying electronic and nonlinear-optical properties of organometallic materials. |

**Awards and Honors**

| | |
|---|---|
| 3/98 | Distinguished Inventor of the Year, awarded by The Intellectual Property Owners Association for the development of stacked multicolor organic LEDs. |
| 11/98 | Thomas Alva Edison Patent Award, presented by the Research and Development Council of New Jersey, for multicolor organic light emitting devices. |
| 12/04 | Raubenheimer Outstanding Faculty Award, College of Letters, Arts and Science, University of Southern California |
| 5/06 | Jan Rajchman Prize for Outstanding Research in Flat Panel Displays, Society for Information Display |
| 11/06 | MRS Medal, Materials Research Society |
| 3/07 | USC Associates Award for Excellence in Research (given to a one faculty member per year) |

**Research Areas:**

Research interests involve the optical and optoelectronic properties of molecular materials and devices, particularly organic LEDs and solar cells, as well as nanoscale materials, catalysis and biosensors.

**Publications and Patents:**

Mark Thompson has over 250 peer reviewed publications, and greater than 120 issued US patents. A detailed list is available at http://met.usc.edu or can be provided at request. A list of recent, relevant papers is given below.

1. Investigation of the thermal stability of 2-D patterns of Au nanoparticles. Ting-Yu Shih, Aristides A. G. Requicha, Mark E. Thompson and Bruce E. Koel, *Journal of Nanoscience and Nanotechnology*, **2007**, *7*, 2863-2869.
2. Actuation of Polypyrrole Nanowires. Alexander S. Lee, Serban F. Peteu, James V. Ly, Aristides A.G. Requicha, Mark E. Thompson, Chongwu Zhou, *Nanotechnology*, **2008**, *19(16)*, 165501/1 – 165501/8.
3. Label-Free, Electrical Detection of the SARS Virus N-Protein with Nanowire Biosensors Utilizing Antibody Mimics as Capture Probes. Fumiaki N. Ishikawa; Hsiao-Kang Chang; Marco Curreli; Hsiang-I. Liao; C. Anders Olson; Po-Chiang Chen; Rui Zhang; Richard W. Roberts; Ren Sun; Richard J. Cote, *ACS Nano*, **2009**, *3(5)*, 1219-1224.
4. High-Performance Single-Crystalline Arsenic-Doped Indium Oxide Nanowires for Transparent Thin-Film Transistors and Active Matrix Organic Light-Emitting Diode Displays. Po-Chiang Chen; Guozhen Shen; Haitian Chen; Young-geun Ha; Chao Wu; Saowalak Sukcharoenchoke; Yue Fu; Jun Liu; Antonio Facchetti; Tobin J. Marks, etal., *ACS Nano*, **2009**, *3(11)*, 3383-3390.
5. A Calibration Method for Nanowire Biosensors to Suppress Device-to-Device Variation. Fumiaki N. Ishikawa; Marco Curreli; Hsiao-Kang Chang; Po-Chiang Chen; Rui Zhang; Richard J. Cote; Mark E. Thompson; Chongwu Zhou, *ACS Nano*, **2009**, *3(12)*, 3969-3976.
6. Continuous, Highly Flexible, and Transparent Graphene Films by Chemical Vapor Deposition for Organic Photovoltaics. Lewis Gomez De Arco; Yi Zhang; Cody W. Schlenker; Koungmin Ryu; Mark E. Thompson; Chongwu Zhou, *ACS Nano*, **2010**, *4(5)*, 2865-2873.
7. Porphyrin-Tape/C60 Organic Photodetectors with 6.5% External Quantum Efficiency in the Near Infrared. Jeramy Zimmerman; Vyacheslav V. Diev; Kenneth Hanson; Richard R. Lunt; Eric K. Yu; Mark E. Thompson; Stephen R. Forrest, *Advanced Materials*, **2010**, *22(25)*, 2780-2783.
8. Importance of Controlling Nanotube Density for Highly Sensitive and Reliable Biosensors Functional in Physiological Conditions. Fumiaki N. Ishikawa; Marco Curreli; C. Anders Olson; Hsiang-I Liao; Ren Sun; Richard W. Roberts; Richard J. Cote; Mark E. Thompson; Chongwu Zhou, *ACS Nano*, **2010**, *4(11)*, 6914-6922.
9. Fused Pyrene-Diporphyrins: Shifting Near-Infrared Absorption to 1.5 Micron and Beyond. Vyacheslav Diev; Kenneth Hanson; Jeramy D. Zimmerman; Stephen R. Forrest; Mark E. Thompson, *Angewandte Chemie (International Ed. in English)*, **2010**, *49(32)*, 5523-5526.
10. A Paradigm for Blue- or Red-Shifted Absorption of Small Molecules Depending on the Site of π-Extension. Kenneth Hanson; Luke Roskop; Peter I. Djurovich; Federico Zahariev; Mark S. Gordon; Mark E. Thompson, *Journal of the American Chemical Society*, **2010**, *132(45)*, 16247-16255.